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Optimization of multiple PON deployment costs and comparison between GPON, XGPON, NGPON2 and UDWDM PON

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ABSTRACT

In this paper we propose an optimization framework for multiple deployment of PON in a wide region with very large number of users, with different bit rate demands, serviced by many central offices, as it may practically happen in a large city that plans a massive introduction of Fiber to the Home technologies using PON. We propose an algorithm called Optimal Topology Search (OTS), which is based on a set of heuristic approaches, capable of performing an optimal dimensioning of multiple PON deployments for a set of central offices (CO), including an optimal distribution of users among the CO. The set of heuristics integrated in OTS permit the efficient clustering of users for each CO, depending on their location and the bit rate demanded by them. It also permits the definition of optimal routes for optical cables and the allocation of branching devices. Taking into account hardware capacity restrictions and physical layer restrictions, we obtained solutions for different types of standardized PON technologies, like GPON, XGPON and NGPON2 as well as for future UDWDM-PON. We evaluate the optimal network deployment in a series of different minimum guaranteed bit rate demand scenarios, employing realistic maps of a large city in order to compare costs and portrait some reference points for deciding in which scenario a specific technology constitutes the best choice.

1. Introduction

The study of next-generation PON technologies is a very popular topic of research in recent years, given the exponential increase of bit rate demands from residential and corporate users [1] and the consequent need of next generation optical access networks with capabilities for supporting such demands [2,3]. Today's worldwide deployment of optical access networks is based either on GPON or EPON and is reaching millions of installations per year. Regarding this type of networks, a widely covered topic of research is the techno-economics study of cost-effective deployment strategies [4]. The massive Fiber-to-the-Home (FTTH) deployment that is forecast to take place in the next few years in several parts of the world will likely be done not only with the currently installed GPON or EPON technology, but also with the other already approved and more advanced standards such as the ITU-T XGPON and NG-PON2 [5]. In the longer terms, even more powerful (in term of overall PON bit-rate capacity) PON solutions have been proposed, such as software defined optical access networks [6] and UDWDM PON [7], which may constitute a promising technology for developing next generation of optical access networks, capable of delivering high bandwidth services to a very large number of users. In addition, many research works propose new technological solutions for implementing low-cost and energy efficient next-generation PON [8,9].

Regarding the study of optimization schemes for dimensioning the optical distribution network (ODN) in PON, the approach most optimization models employ is a green-field design-planning model for searching the minimum-cost tree-topology for a set of fixed residential or corporate users [10]. Some research works cover the study of optical distribution networks for connecting mobile base stations with the central office equipment [11]. The ODN cost mostly evaluates the capital expenditures (CAPEX), related with the optical fiber and switching equipment costs, and some models consider also the operational expenditures (OPEX) [12].

We briefly review here some of the existing literature on the general problem related with the optimal dimensioning of an ODN. Usually, it is confronted as an integer linear programming (ILP) or mixed integer linear programming (MILP) optimization problem [13], subject to different types of restrictions based on the optical fiber length and on switching equipment amount and capacity (among other physical

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restrictions like the systems' power budget and flow aggregation) [14,4].

Under the general conditions regarding the PON's ODN deployment in a geographical region, the set of links connecting a set of points (i.e. connecting every OLT transceiver with a set of cascaded splitters and finally with the ONU) can be modeled as a weighted-bounded graph [15]. Hence, the problem related with the optimal topology search for connecting the users' end equipment with the provider's equipment can be considered essentially a weighted Steiner tree problem [16], which is a well-known NP-hard problem [17]. Therefore, some heuristic approach is generally employed in order to find a feasible near-optimal solution in polynomial time for the linear-programming (LP) modeled optimization problem [18,19].

Some relevant research works have employed ILP and heuristic approaches for finding solutions to network-planning models in the field of the next generation optical access networks, like the work reported by D. Truong et al. in [20] where authors propose a survivable TWDM PON based in mesh topologies. In [21] M. De Andrade et al. describe an optimization scheme for WDM PON technology selection based on an ILP model. In addition, other research works propose ILP models combined with heuristics for finding optimal topologies in greenfield scenarios, like the work presented by Li et al. [4].

In this paper we develop an ILP-based optimization problem for scenario in which a very large number of users (of the order of 10^5) should be FTTH connected using PON technologies. We thus do not focus only on a single PON tree (that can reach 64 users at most using today standards, and likely 256 users with UDWDM-PON) but on the global optimization of multiple PON deployment, typically optimizing the placement of thousands of PON trees connected to several Central Offices. We strive to be as practical as possible, thus using real city maps and thus street aware optimal topology solutions, assuming to place fiber ducts only along existing streets. Moreover, for the physical layer constraints (such bit rate, splitting ratio, losses, etc) we use exactly the values reported in the relevant ITU-T standards. Finally, for the CAPEX costs we made realistic assumptions that come from interaction with operators and vendors. The main goal of this paper is twofold:

- we want to propose a novel heuristic approach that can work on such a complex optimization problem;
- we want to apply it to study the techno-economics of different PON technologies under very different bit rate requirements, ranging from the typical bit rates that are given today to broadband users (i.e. several tens of Mbit/s sustained per user) up to much higher future requirements. Moreover, we also want to differentiate the traffic demands between residential users and business users.

To the best of our knowledge, no other research work report a street-aware optimal dimensioning of multiple PON for a very large number of users comparing the costs of standardized types of PON like GPON, XGPON, NGPON2 and UDWDM PON.

The remaining of this paper is organized as follows. In Section 2 we discuss the scenario and reference costs employed in the analysis. Section 3 presents the details of the problem formulation, including notations and parameter values as well as the algorithm and heuristic approaches employed for finding a solutions to the optimization problem. Section 4 describes the most relevant results obtained with the model proposed in the paper remarking the costs comparison between the multiple UDWDM PON deployment with the deployment of other standardized PON technologies. Finally, Section 5 concludes this paper.

2. Scenario and costs

2.1. Scenario

There are different topology proposals for next-generation optical-access-network [22] but the predominant one for large FTTH deployment is today the PON topology, which is the well-known optical tree topology based on optical splitters. This paper focuses on FTTH deployment planning using only PON, for which we briefly review here the most relevant ITU-T standards. GPON and XGPON can reach up to 64 users employing Time-Division Multiplexing (TDM) as the channel-sharing technique [23,24]. The recent NGPON2 standard [25] introduced for the first time in PON standard an hybrid TDM/WDM transmission employing four or more DWDM wavelengths for downstream (DS) and for upstream (US), keeping compatibility with legacy ODN [26]. The IEEE PON standards, not mentioned here only for space limitations, have followed a similar evolution towards higher overall capacity in recent years.

The scenario we use for testing our optimization algorithm is the deployment of multiple passive optical access networks in a metropolitan region of about 25 km^2 with a very large number of users. In order to test our planning model we have chosen different simulation scenarios all of them with about 10^5 users. In addition, a region with such amount of users requires the support of multiple Central Offices (CO). Every CO houses the hardware necessary to service all users inside its subregion, and is thus equipped with a large number of optical line terminals (OLT). In order to start introducing the order of magnitude of these numbers, we anticipate that the following Sections will apply our optimization algorithms to 10^5 users connected to five central offices, so that every CO will have to host on average 2×10^4 users and thus many OLT chassis with tens OLT line cards holding (jointly) hundreds of OLT transceivers.

We assume that the interconnection among CO is performed by a metropolitan optical fiber ring whose study is anyway beyond the scope of our work. Additionally, we consider every CO constitutes the root of a multiple tree-topology (i.e. every CO's tree-topology is connected with other CO's tree-topologies through the metropolitan interconnection ring). PON splitters are distributed along the streets among a series of primary street cabinets (PSC), which are placed in publicly accessible places like sidewalks, corners, parks, etc., and secondary street cabinets (SSC), which are placed in any building where al least one user must be connected. A set of multi-fiber feeder optical cables connect a CO with its correspondent PSC. The connection between PSC and the correspondent SSC is performed by means of distribution optical fiber (OF) cables. In a SSC there's one or more splitters (depending on the number of PON required to service the users inside the respective building). From the SSC it is routed a single OF connection up to each users' optical network units (ONU). Fig. 1 illustrates a general schema of the multiple PON topology employed in this study.

We focus our analysis in the comparison of deployment costs using different PON technologies (GPON, XGPON and NGPON2 and the more future-oriented UDWDM PON). While for the existing standards the physical parameters were well known and in some ways also the cost estimate can be obtained from vendors, the situation is less clear for UDWDM-PON, so that for the physical layer we took most data from this paper [7], and for the cost we made some reasonable assumptions, as shown in the last section of the paper.

In order to consider a real scenario for our street-aware optimization algorithm, we developed an ad-hoc interface for retrieving real streets and buildings data from OpenStreetMaps (OSM) database [27]. In order to present a specific deployment scenario of costs, we have chosen a down town zone of Turin, Italy, selecting a region characterized by the presence of many residential buildings. Buildings in this zone may have few residential apartments, tens of apartments and even some hundreds of apartments. We use a region of 15 km^2 with nearly 6500 buildings and a total number of users in the order of 10^5 users. The street and building location that we used in our optimization tool corresponds exactly to the real data taken from the OSM database while we did some reasonable assumptions to estimate the actual number of users per building (a data that is not directly available in OSM, but that we statistically derive using such information as the building footprint and number of floors). Moreover, we assumed that the corporate users in Turin's selected region is a 2% of the total users.

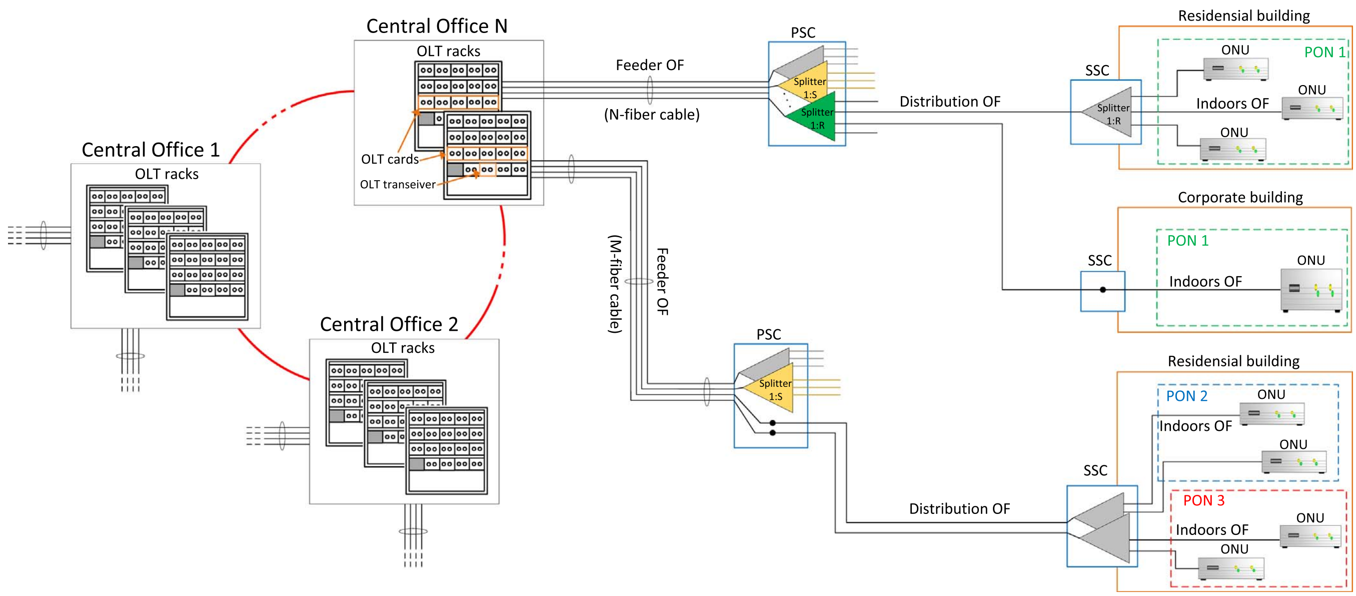

Fig. 1. Schema of a multiple PON deployment.

Table 1
Costs of OF cable and trenching (prices are expressed in United States Dollars - USD).

Component	Cost (USD)
Feeder Cable, 2 fibers/km	600
Feeder Cable, 4 fibers/km	800
Feeder Cable, 6 fibers/km	1000
Feeder Cable, 12 fibers/km	1500
Feeder Cable, 24 fibers/km	2000
Feeder Cable, 48 fibers/km	2500
Feeder Cable, 64 fibers/km	3000
Feeder Cable, 96 fibers/km	3500
Feeder Cable, 144 fibers/km	3700
Feeder Cable, 288 fibers/km	4000
Distribution Cable/km	2000
Indoor OF installation/user	50
Trenching and reinstatement/km	30,000
Ducts and fenders/km	10,000
Fusions and slicing/unit	10
Manholes/unit	500

Table 2
Costs of cabinets (prices in USD).

Component	Cost ($)
Junction box 144 OF	500
Junction box 48 OF	400
Junction box 16 OF	350
Junction box 8 OF	300
1:64 splitter	120
1:32 splitter	70
1:16 splitter	45
1:8 splitter	28
1:4 splitter	24
1:2 splitter	20
Cabinet installation	1600

2.2. Reference costs

In order to evaluate the deployment cost of multiple PON, we have employed data directly from a telecom operator and from an equipment vendor. Even though the prices between operators and vendors may vary among them, the competitiveness of the telecommunications market makes the prices among different operators and vendors are similar enough for working, as in this case, using a single reference for the prices. Any way, as it will be evidenced later, our optimization framework may be used also for comparing different vendors' solutions.

Therefore, for GPON and XGPON hardware we employ real updated market prices. In the case of NGPON2, the consulted equipment vendor confirmed that the prices of hardware (OLT and ONU hardware) for that technology would be, according to the usual behavior of prices for new technology products, approximately two fold in comparison with the latest technology (i.e. in this case two fold the prices of XGPON). We also employed this consideration for UDWDM PON technology (i.e. prices in the order of two times the prices of NGPON2). This trend of price growth for new technology hardware can in fact be appreciated in the prices of XGPON vs GPON (approximately two times the prices of the former in comparison with the prices of the latter). Nevertheless, UDWDM PON prices might be even greater due to it needs coherent transceivers, high speed DSP and tight control of the transmitter laser and the receiver optic front. In addition, UDWDM PON would mean new design in the PON industry and new training to the installation staff. Therefore, as it is detailed in Section 4 of this paper, we even consider the price of UDWDM PON as a variable increasing from tree times the currently known costs of XGPON up to five times the costs of XGPON.

In the network planning model reported in [21] authors propose a complexity-based cost function for assuming the hardware price of non-commercially available technologies like Tunable TDM/WDM PON and Colorless WDM PON. Table 1, shows the reference costs we employ for optical-fiber cable and related labor, including the cost of trenching, reinstatement and manholes (employed for the OF cable installation and further maintenance). Table 2 details costs for splitters and cabinets and Table 3 specifies costs of hardware for the different type of PON considered in this paper.

3. Problem formalization

3.1. Notations and variables

Any city's region where a multiple PON topology must be deployed can be treated as a weighted connection graph. In this graph streets and street-intersections constitute edges and points which can be used as routing paths from the central offices up to their respective PSC, and from PSC up to the SSC. Now, focussing in a subregion constituted by a

Table 3
Costs of PON hardware and related labor (prices in USD).

Component	Cost ($)
OLT chassis - GPON (10^3 users)	16,000
OLT chassis - XGPON (10^3 users)	28,000
OLT chassis - NGPON2 (10^3 users)	50,000
OLT chassis - UDWDM PON (10^3 users)	85,000
OLT card - 8xGPON	9000
OLT card - 8xXGPON	15,000
OLT card - 8xNGPON2	25,000
OLT card - 8xUDWDW-PON	40,000
ONU residential - GPON	100
ONU residential - XGPON	350
ONU residential - NGPON2	600
ONU residential - UDWDM PON	1100
ONU corporative - GPON	350
ONU corporative - XGPON	600
ONU corporative - NGPON2	1100
ONU corporative - UDWDM PON	2200
Splicing/per splice	10
OLT installation	2000
ODF (for each OLT rack)	3500

single CO, which must be connected to all its serviced users, the objective is to find a topology graph that is optimal under the cost targets that we will describe in detail later in this section.

In order to describe the optimization problem we first define some notations for a set of required parameters, variables and constants as described in Tables 4 and 5.

Also, we employ sets of parameters regarding sites, physical paths and costs. Let's say that in the city's region under study, ST is the set of streets, including any physical path suitable for trenching (i.e. for routing the OF cables) and BL is the set of buildings (i.e. any place where users demand connectivity to the PON topology). This parameters are defined in Table 6.

In addition, the optimization model requires the definition of the binary variables defined in Table 7.

3.2. Network parameters and users demands

In this subsection we present a brief description of the network parameter settings we employ for each PON technology, based on the values established in each correspondent standard. Table 8 shows the specific network parameters for each PON technology. In our analysis

Table 4
General sets and variables that are referenced in the problem formalization.

Set	Description
CO	The Central Offices' set, $CO = \{CO_c\}$, with $c \in \{1, 2, \ldots, C\}$; where C is the number of available central offices.
N_c	The number of users serviced by central office c, in such a way that $\sum N_c = N$, where N is the total number of active users (i.e. the number of ONU) in the region.
O	The set of OLT transceivers, with $o \in \{1, 2, \ldots, M\}$, where M is the number of available OLT transceivers.
U	The ONU set, with $n \in \{1, 2, \ldots, N\}$, where N is the number of ONU.
W	The wavelengths set, with $w \in \{1, 2, \ldots, L\}$; where L is the number of available wavelengths in one OLT transceiver (per direction). For instance L=1 for GPON and XGPON, while it can be up to L=256 for UDWDM-PON.
L_i	The set of splitters available in cabinet placed at the site i. We also define $S_{i,l}$ as the l^{th} splitter, in the cabinet i, whose splitting ratio (SR) is given by $K_{i,l} = 2^r$, where r is a positive integer number.
r_i	The enclosure's capacity of a cabinet placed at the site i.
B	Is the set of candidate sites for location of SSC.
V	Is the set of candidate sites for location of PSC.
n_{max}	Is the maximum number of users per each OLT transceiver.
ODN_{loss}	The maximum loss, in dB, allowed in the ODN.

Table 5
Parameters related with PON capacity and users' bit rate demands.

Parameter	Description
BR_{ref}	Reference bit rate (for normalization purposes).
BR_{US}/λ	The total upstream (US) bit rate capacity per each OLT transceiver wavelength.
BR_{DS}/λ	The total downstream (DS) bit rate capacity per each OLT transceiver wavelength.
BR_{US}^n	The US bit rate demanded by ONU $n \in U_c$.
BR_{DS}^n	The DS bit rate demanded by ONU $n \in U_c$.
Γ_{US}	The normalized total OLT's transceivers US bit rate capacity, $\Gamma_{US} = (L \cdot BR_{US}/\lambda)/BR_{ref}$.
Γ_{DS}	The normalized total OLT's transceivers DS bit rate capacity, $\Gamma_{DS} = (L \cdot BR_{DS}/\lambda)/BR_{ref}$.
γ_{US}^n	Normalized US bit rate demanded by ONU $n \in U_c$, $\gamma_{US}^n = BR_{US}^n/BR_{ref}$.
γ_{DS}^n	Normalized DS bit rate demanded by ONU $n \in U_c$, $\gamma_{DS}^n = BR_{US}^n/BR_{ref}$.

Table 6
Parameters of sites, physical paths and costs.

Parameter	Description
I	Set of street' (intersections) nodes and buildings' nodes (vertices), $I = \{i \in \{ST, BL\}/i = 1, 2, \ldots, T\}$; where T is the number of nodes in streets and buildings.
E	Set of edges $E = \{e_{i,j} \in E/(i, j) \in I\}$.
$a_o{}^c$	is a binary constant that indicates if the OLT o is placed at the central office c with a value of 1.
$d_{i,j}$	The distance between two points $(i, j) \in I$. If the points are joined by a single edge, it is the length of the edge. If not, $d_{i,j}$ is the minimum end to end distance calculated by an optimal routing algorithm through several streets and intersections.
$C_{OF}{}^f$	Cost, per unit length, of a feeder OF cable.
$C_{OF}{}^d$	Cost, per unit length, of a distribution OF cable.
C_T	Cost of trenching, per unit length.
$C_{encl}{}^r$	Cost of a street cabinet enclosure with capacity for installing up to r splitters.
$C_{i,l}$	The cost of the l^{th} splitter it the cabinet placed at site i.
$C_{OLT}^{rck,\eta}$	The cost of an OLT's rack with capacity for η users.
$C_{OLT}{}^{crd}$	The cost of an OLT's transceiver.
C_{ODF}	The cost of an optical distribution frame (ODF).
C_{ONU}	The cost of an ONU.
$C_{lbr}{}^c$	The cost of labor (i.e. splicing, hardware installation, cabling) in a CO.
α_{FO}	The optical fiber attenuation per unit length.
$\alpha_{i,l}$	The attenuation of the l^{th} splitter placed in the cabinet i.
α_{ex}	Other losses in the ODN.

Table 7
Binary variables employed in the optimization problem formulation.

Variable	Description
$x_{n,j}$	Is equal to 1 if the ONU n is connected to the SSC located in site j; otherwise is 0.
$x_{j,i}$	Is equal to 1 if the SSC on site j is connected to the PSC located in site i; otherwise is 0.
$x_{i,o}$	Is equal to 1 if a splitter on the PSC placed on site i is connected to the OLT transceiver o; otherwise is 0.
a_i	Is equal to 1 if the candidate site $i \in \{V \cup B\}$ is active; otherwise is 0.
a_o	Is equal to 1 if OLT transceiver o is active; otherwise is 0.
$S_{i,l}$	Is equal to 1 if the lth splitter on site i is active; otherwise is 0.
$y_n^{j,l}$	Is equal to 1 if the ONU n connects to the lth splitter placed on site j; otherwise is 0.
$y_{j,l}^{i,p}$	Is equal to 1 if the lth splitter located on a SSC placed at site j connects to the pth splitter located on a PSC placed at site i; otherwise is 0.
$z_n{}^o$	Is equal to 1 if ONU $n \in U$ is connected to OLT o; otherwise is 0.

we focus on the downstream (DS) transmission because it constitutes the most demanding scenario for the multiple PON dimensioning given that users usually require more bit rate in the DS direction. In the case

Table 8
Network parameters for GPON, XGPON, NGPON2 and UDWDM PON.

Parameter	PON Technology			
	GPON	XGPON	NGPON2	UDWDM PON
Max. link length [km]	40	40	40	100
Max. ODN loss [dB]	35	35	35	43
Users per OLT transceiver	64	64	64	256
Number of wavelengths	1	1	4	256
DS bit rate per OLT [Gb/s]	2.5	10	40	256

of UDWDM-PON, we set the parameters based on the work reported by Rohde et al. [7], with few variations in order to be more conservative. For instance, in Rohde's proposal a single OLT is able to service up to 1024 users with a bit rate of 1 Gb/s; instead, we assume that each OLT transceiver is capable of servicing only up to 256 users with the same bit rate of 1 Gb/s. Such variation is made in order to have an approach to an UDWDM PON more conservative in terms of capacity.

Other general network parameters we use are:

- Type of OF: SSMF G652.
- Type or branching device: optical power splitters.
- Attenuation in splitters with splitting ratio $k = K_{i,l}$: $\alpha_{i,l} = 3.5\log_2(k)$ dB [25].
- Maximum number of cascaded splitters: 2.
- Type of users: Residential and Business.
- Number of users in the covered region: N=10^5.
- Reference bit rate (for normalization): BR_{ref}=10 Gb/s.

In the case of the users' bit rate demands, we consider six scenarios where residential and corporate users increase the demand of minimum guaranteed bit rate from few tens of Mb/s up to many hundreds of Mb/s [1] and even up to one or more Gb/s (in order to include a long-term scenario). We do not focus on peak rates due to the very low probability that all users at the same time generate peak rate requests; thus, se consider that the peak rate requests would be successfully attended by the available PON hardware. Table 9 details the six scenarios of bit rate demands we employ in the analysis. In each scenario we defined a bit rates interval for residential and for business users. As further explained later, for each user we randomly generate the actual bit rate request inside the specified interval, using a uniformly distributed probability function, and we interpreted it as a minimum guaranteed bit rate that each user *must* be given.

3.3. Optimization problem formulation

The objective function of the optimization problem formulation aims to minimize the total deployment cost of the multiple PON scenario. The function covers the deployment costs in each one of the CO subregions. A main consideration of the problem is the clustering of users among CO based on combinatorial variation of users, i.e. users may be freely distributed among the different CO in order to find the optimal distribution, which constitutes the main advantage of solving the problem for the entire wide region, instead of solving each CO's region as an independent problem. As further explained, in our heuristic approach we confront this combinatorial problem as a random search moving buildings among CO, in a cost-optimization sense, trying to keep approximately N/C users in each CO region, where C is the number of available CO.

Table 9
Bit rate scenarios employed in the analysis.

Scenario	Intervals of demanded bit rate [Mb/s]	
	Residential users	Corporate users
1	10–50	100–500
2	50–100	500–1000
3	100–400	1000–2500
4	100–1000	1000–10000
5	500–2500	2500–10000
6	1000–2500	5000–40000

The objective function is defined by Eq. (1).

$$\begin{aligned} \min \quad & \sum_{c\in CO}\Bigg(C^c_{lbr} + C_T\Bigg(\sum_{o\in O}\sum_{i\in V}\alpha^c_o x_{i,o}d_{i,o} + \sum_{i\in V}\sum_{j\in B}\alpha^c_o x_{j,i}d_{j,i}\Bigg) + C^f_{OF} \\ & \sum_{o\in O}\sum_{i\in V}\alpha^c_o x_{i,o}d_{i,o}\Bigg) \\ & +C^d_{OF}\Bigg(\sum_{i\in V}\sum_{j\in B}x_{j,i}d_{j,i} + \sum_{j\in B}\sum_{n\in U}x_{n,j}d_{n,j}\Bigg) + \sum_{i\in V\cup B}\sum_{l\in L_i}S_{i,l}C_{i,l} + \\ & \sum_{i\in V\cup B}C^r_{encl}\alpha_i \\ & +\frac{N}{\eta}(C^{rck,\eta}_{OLT} + C_{ODF}) + \sum_{o\in O}C^{crd}_{OLT}\alpha_o + C_{ONU}N \end{aligned} \tag{1}$$

Eq. (1) is composed by a global sum operation of the cost for every deployment-component, with respect to each CO. Inside the global sum, the first component take into account costs of the labor related with OF and hardware. Next, there are three components regarding the costs of trenching and the cost of feeder and distribution OF cables. Following there are two components for the costs of the cabinets' enclosures and splitters for PSC and SSC, respectively. The last three components of the function cover the cost of PON hardware. The first and last three terms are actually fixed but we include them in the objective function in order to provide a full evaluation of the total deployment cost.

The constraints that ensure the ILP problem complies with the requirements of the proposed optimal network planning, in a real scenario, are the following.

- The variable which defines the path between an OLT o and an ONU n is evaluated as:

$$z^o_n = \sum_{i\in V}\sum_{j\in B}x_{n,j}x_{j,i}x_{i,o} \quad \forall\ n\in U, \forall\ o\in O \tag{2}$$

- Every user must be connected to only one c ∈CO. Thus, the sum of users connected to each c ∈CO must be equal to the total number of users in the whole region:

$$\sum_{c\in CO}N_c = N; \tag{3}$$

- The number of users connected to a central office c ∈CO is evaluated as:

$$N_c = \sum_{n\in U}\sum_{o\in O}\alpha^c_o z^o_n; \quad \forall\ c\in CO \tag{4}$$

- The number of users (ONU) per each OLT transceiver must be at most n_{max}:

$$\sum_{n\in U}z^o_n \le n_{max}\alpha_o; \quad \forall\ o\in O \tag{5}$$

- The maximum bit rate demand per each OLT transceiver must not be greater than its per-wavelength US and DS capacity Γ:

Table 10
Description of the OTS's secondary functions.

Function	Description
allocatessc()	Identifies users in each building (i.e. if there is a business or residential user demanding connection to the PON) and assigns a SSC to the building selecting the closest node of the building with respect to the nearest street.
clustrbuild()	Clusters the users of a CO sub-region by means of assigning one or more PON to a given set of buildings (i.e. depending on the number of users and the aggregated bit rate demand inside a building it dimensions the correspondent OLT's and ONU's hardware). The clustering algorithm we employ is a Shared Nearest Neighbor (SNN) based clustering algorithm [30], which permits a more efficient clustering than the traditional *k*-means algorithm because it can be tailored for clustering buildings instead of single users. We use the SNN algorithm in such a way that every building is treated as an entity with a distance based on numerical and categorical attributes. Therefore, the distance is evaluated based on the combination of the Euclidian length from the building up to the closest PSC or CO, with the attributes of the building. The numerical attributes of a building are: *i*) the number of users inside the building and *ii* the normalized total amount of traffic demanded by those users. The categorical attribute of a building defines if it is: *i*) a residential building or *ii*) a corporate building.
aggregate()	Performs PSC dimensioning and allocation by means of PON aggregation, from a set of initial candidate sites for PSC and a Tabu search heuristic which changes the PSC positions based on the closest single move towards the CO given by the Delaunay's triangulation of the current PSC locations.
findpaths() *share*()	These functions evaluate the trenching, duct sharing and searching of optimal routes for OF cables from CO up to PSC and from PSC up to SSC, by means of a modified Dijkstra's algorithm which uses the recursiveness of a path as criterion for the best route.
evaluatecots()	Evaluates the cost of the multiple PON deployment from the results given by the previous functions. The cost of the OF cabling from SSC up the users' ONU inside every building is calculated based on the average number of the levels in the building, for vertical-cabling dimensioning, and on the average radius of the buildings' geometrical skull, for the horizontal-cabling dimensioning.

$$\sum_{n\in U} z_n^o \gamma_{US/DS}^n \le \Gamma_{US/DS}\alpha_o; \quad \forall\ o\in O \tag{6}$$

- An ONU must be connected to only one splitter, which is placed in an enclosure at site j:

$$\sum_{j\in B} x_{n,j} = 1; \quad \forall\ n\in U \tag{7}$$

- A site where a SSC is located must connect to only one site with a PSC if the SSC is active:

$$\sum_{i\in V} x_{j,i} = \alpha_j; \quad \forall\ j\in B \tag{8}$$

- A site where a PSC is located must connect to a single OLT transceiver if the PSC site is active:

$$\sum_{o\in O} x_{i,o} = \alpha_i; \quad \forall\ i\in V \tag{9}$$

- The number of active splitters on site i must be less than the site enclosure capacity:

$$\sum_{l\in L_i} s_{i,l} \le \alpha_i r_i; \quad \forall\ i\in\{V\cup B\} \tag{10}$$

- An ONU can connect to a splitter on site i if there is a physical connection between the ONU and the site i:

$$y_n^{i,l} \le x_{n,i}; \quad \forall\ i\in\{V\cup B\}, \forall\ n\in U, \forall\ l\in L_i \tag{11}$$

- A splitter on a SSC located on site j can only connect to a splitter on a PSC located on site i if there is a physical connection between both sites:

$$y_{j,l}^{i,l} \le x_{j,i}; \quad \forall\ i\in V, \forall\ p\in L_i, \forall\ j\in B, \forall\ l\in L_j \tag{12}$$

- The number of ONU that can connect to the l^{th} spliter on a SSC located at site j can not exceed the spliter capacity if the splitter is active:

$$\sum_{n\in U} y_n^{j,l} \le K_{j,l}S_{j,l}; \quad \forall\ j\in B, \forall\ l\in L_j \tag{13}$$

- The number of ONU and the number of splitters located on any SSC that directly connect to the p^{th} spliter on a PSC located at site i can not exceed the spliter capacity if the splitter is active:

$$\sum_{n\in U} y_n^{i,p} + \sum_{j\in B}\sum_{l\in L_j} y_{j,l}^{i,p} \le K_{i,p}S_{i,p}; \quad \forall\ i\in V, \forall\ p\in L_i \tag{14}$$

- The power losses in a link from an OLT up to an ONU must be lower or equal than the PON's allowed ODN loss.

$$\begin{aligned}&\alpha_{FO}\left(\sum_{j\in B} x_{n,j}d_{n,j} + \sum_{i\in V}\sum_{j\in B}\sum_{o\in O} x_{n,j}x_{i,o}x_{j,i}d_{j,i} + \sum_{i\in V}\sum_{o\in O} x_{i,o}d_{i,o}\right)\\ &+\sum_{j\in B}\sum_{l\in L_j} y_n^{j,l}S_{j,l}\alpha_{j,l} + \sum_{i\in V}\sum_{p\in L_i}\sum_{j\in B}\sum_{l\in L_j} y_n^{j,l}y_{j,l}^{i,p}S_{i,p}\alpha_{i,p} + \alpha_{ex}\\ &\le ODN_{loss}; \quad \forall\ n\in U\end{aligned} \tag{15}$$

3.4. Optimization framework

The problem described by Eq. (1) and its correspondent constraint equations constitute a Minimal-Steiner-Tree optimization problem, which is NP-hard [17]. Then, in order to find a solution for a very large number of users we propose an heuristic approach based on a Primary Function (PF) and a set of secondary functions (SF), which are described in detail in Table 10. We have named it "Optimal Topology Search" (OTS).

PF first loads the OSM data of the city (i.e. streets' and buildings' data), asks for a set of Central Offices' (CO) in the map, and using a uniformly distributed random function generates the users' data (i.e. position and bit rate demands). Then, it clusters the region in a CO-basis starting from a Voronoi's tessellation of the total region using a k-means algorithm [28] for dividing the region in C zones, where C is the number of central offices. Here the center of a CO region is a geometrical center and do not necessarily corresponds to the location of the CO building. Once OTS has completed the optimal topology cost for this first clustering set, using the set of secondary functions SF, it changes the clusters by means of moving buildings from one CO region to other CO region based on the variation of the region's geometrical center towards the geographic position of the correspondent CO building.

Therefore, PF recursively evaluates the total multiple-PON topology cost in each iteration comparing the new cost with the previous one and discarding the higher-cost topology. This procedure of iteratively improving the optimal topology cost, using adaptive memory, constitutes a Tabu-search heuristic [29]. The general operation of OTS is described in Algorithm 1.

Algorithm 1. Optimal Topology Search (OTS).

```
Data: Data = load_data(City, Users, CO)
Result: Optimal_Topology = OTS(Data)
begin
    for i ∈ {Heuristic_modifier_counter} do
        Data_i = i^th_heuristic_variation(Data)
        Data_c = cluster_CO_zones(Data_i)
        for c ∈ CO do
            SSC = allocate_ssc(Data_c)
            [OLT, ONU] = clustr_build(SSC, Data_c)
            PON_hardw = {OLT, ONU}
            PSC = aggregate(PON_hardw, Data_c)
            SC = {SSC, PSC}
            OF_feeder = find_paths(PSC, Data_c)
            OF_distrb = find_paths(SSC, Data_c)
            ODN = {OF_feeder, OF_distrb, SC}
            Trenching = share(ODN)
            Topology_i = {ODN, PON_hardw}
        end
        C_i = evaluate_cost(Data_c, Topology_i)
        if C_i < C_opt then
            Optimal_Topology = Topology_i
            C_otp = C_i
        end

    end
end
```

4. Results

We employed the same set of users for all PON technologies, with their corresponding bit rate demands, and the same CO locations in the region chosen for performing the multiple PON deployment tests.

We ran OTS for every PON technology specified in Table 8, sweeping the six bit rate demand scenarios detailed in Table 9. In each case OTS found an optimal topology according to the procedure described in detail in the previous section.

Fig. 2 shows a composite plot of a region in Turin with approximately 10^5 users, using different colors for the initial clustering of users to different central offices and the resulting optimal topology solution found by OTS, for UDWDM PON and bit rate scenario #4 (see later for more details on this). In the amplified areas above we show, as an example of the OTS CO's clustering, the frontier of three different CO clusters. In the amplified area below it can be appreciated in more detail the fact that OTS is a street-aware algorithm which finds, among other non-graphical results, the optimal location of PSC, SSC and routes for feeder and distribution OF cables (illustrated as red lines in the streets), along through the city's streets. For visibility purposes we have not included the plot of links from SSC up to users inside each building.

In a real-life case, users demand different bit rates depending on their needs and preferences. For that reason we randomly assigned, by means of a uniformly distributed random function, a different minimum guaranteed bit rate for each user, residential or corporative, in the range of the correspondent values of the bit rate scenario under consideration. Table 11 specifies the total deployment cost of for GPON, XGPON, NGPON2 and UDWDM PON in every bit rate scenario. An interesting value of the obtained results is the cost of GPON for the bit rate scenario #1, which is approximately the scenario that covers today's typical bit rate demand for residential and corporative users. Such value, 51.4 millon of USD for 10^5 users, corresponds to a cost of about 514 USD per user (i.e 51.4 millon of USD divided by 10^5 users), which seems a reasonable result considering the typical cost estimations of current operator's real costs per user for GPON.

The results in Table 11 show that, for increasing bit rate demands (i.e. going from Bit Rate Scenario #1 up to #6 in our formalization) the deployment cost significantly ramps up above a given bit rate demand “threshold”, whose position depends on each technology capacity. For instance for GPON, the cost ramps up above scenario #2, that requires up to 100 Mbit/s sustained bit rate per user which, given the GPON 2.5 Gbps downstream bit rates, requires to deploy PON having significantly less than 64 users. Basically, this requirement leads to the necessity of deploying a larger number of PONs for the same total number of users, thus significantly increasing cost. As another example, for NG-PON2, thanks to a much higher capacity, the cost ramps up only above Bit Rate Scenario #4.

Fig. 3 shows a chart of costs for each PON technology deployment, including a detail of the cost of hardware, trenching and ODN components, for the six bit rate scenarios. It can be seen in the figure that when the guaranteed bit rate demand from users is relatively low, i.e. in the order of some tens of Mb/s for residential users and some hundreds of Mb/s for corporative users, like in the scenarios 1 and 2, the cost of GPON is the lowest one in comparison with the cost of the other technologies. Instead, when the bit rate demands from residential users is in the order of few hundreds of Mb/s (scenario 3), XGPON becomes the best choice in front of the increased cost of the deployment for GPON and the still more expensive cost of NGPON2 and UDWDM PON. However, as can be seen for the scenario 4, if the bit rate demands of residential users are in the order of few hundreds of Mb/s up to 1 Gb/s and for corporate users in the order of 1 up to 10 Gb/s, then XGPON becomes also an expensive solution in comparison with NGPON2. Under the consideration we have made about of hardware prices for UDWDM PON, which is about two times the price of NGPON2 hardware and about 4 times the prices of XGPON hardware, in scenario 5 NGPON2 still constitutes a better solution than UDWDM PON, and only in scenario 6 the deployment of UDWDM PON has a similar cost to the deployment of NGPON2. Clearly, Scenario 6, where residential users demand a bit rate of 1 or more Gb/s and corporate users demand bit rates beyond 5 Gb/s, is a long term scenario but it may anyway become interesting in the following years.

The increase in the cost of a multiple PON deployment is mainly due to the fact that when the bit rate demands from users overwhelm the capacity of the OLT transceivers of a given technology, the amount of OLT hardware must be incremented in order to support such demands and, as a result, the amount of cost of feeder optical cables and cabinets is also increased. For example, in Fig. 3 it can be seen that the cost of GPON deployment increase is much higher between scenarios 2 and 3 than scenarios 1 and 2, because in scenario 2 the bit rate demands are still in the range of values that do not overwhelm the capacity of GPON transceivers.

Analyzing our results, we see that the most important factor for the increase of the total hardware cost is related to the CO hardware. To

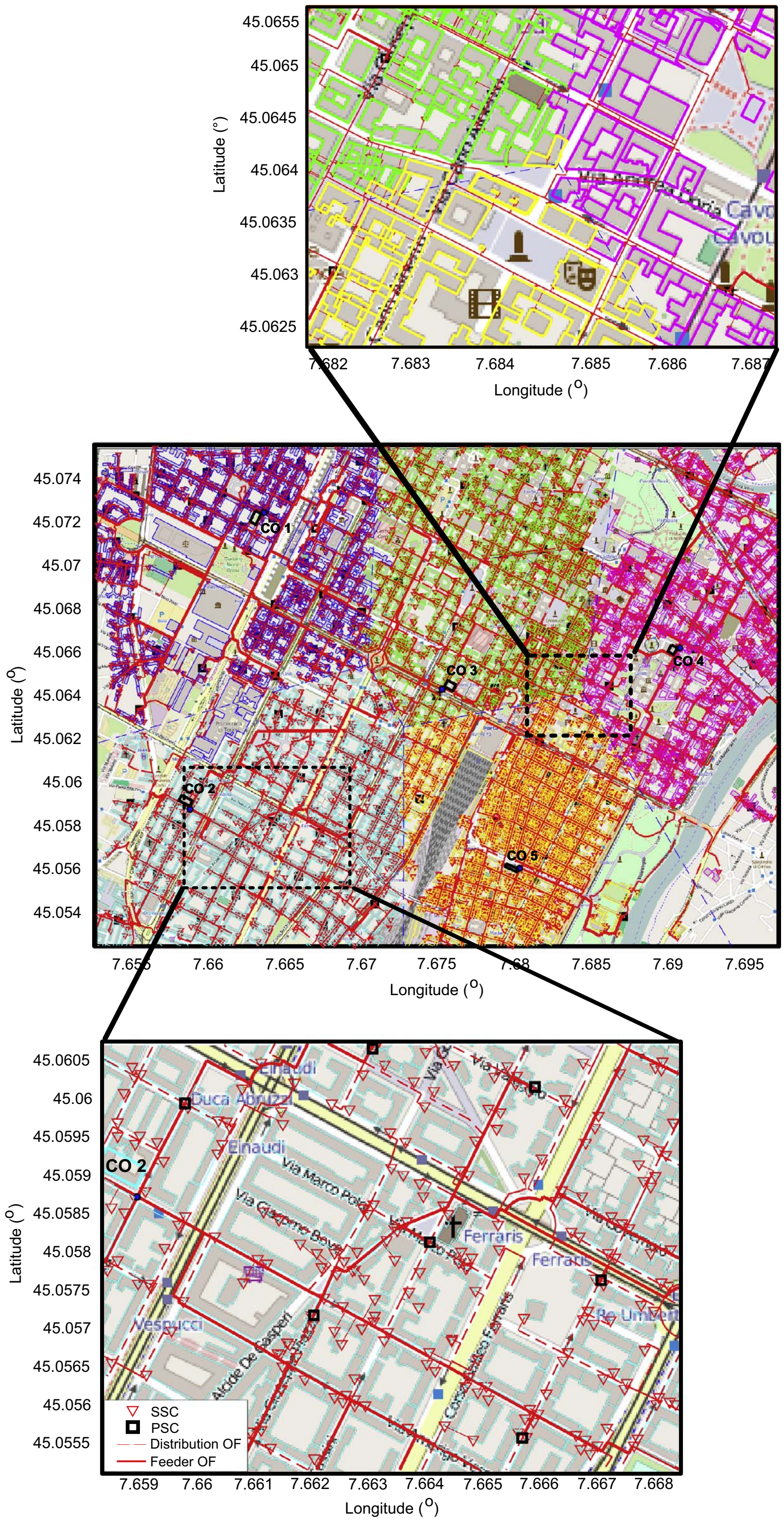

Fig. 2. Illustration of a multiple PON deployment given by OTS algorithm for a region that covers 10^5 users divided in 5 Central Offices' zones (central figure). Zoom above shows the edges of three different CO zones and the correspondent Delaunay's partition. Buildings in different zones are plotted with different color. Zoom below shows a region with about $5{\cdot}10^3$ users which includes the plotting of the feeder and distribution OF cables routing and the locations of the street cabinets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

better point out this result, we plot in Fig. 4 the costs of CO hardware for each PON technology. Notice that, due to its capacity for servicing much more users per OLT, the CO hardware for UDWDM PON is overall less costly in a multiple deployment in comparison with the cost of the other PON technologies. Moreover its price is constant in the first four bit rate demand scenarios, and increases only in the fifth and the sixth scenario, but its increase is much lower than the increase of costs for the other PON technologies. These results confirm the fact that a key point for rendering this technology commercially competitive is the reduction of the ONU's cost.

Table 11
Costs of the multiple PON deployment for 10^5 users.

Bit Rate Scenario	Cost (millon of USD)			
	GPON	XGPON	NGPON2	UDWDM PON
1	51.4	82.2	113.3	157.1
2	61.0	84.2	113.3	157.1
3	106.6	93.3	113.3	157.1
4	178.7	127.9	113.3	157.1
5	394.6	207.8	146.8	159.9
6	–	250.7	168.3	164.5

Even though the cost of the ODN is mostly impacted for the high cost of installation of the distribution optical fiber cables inside buildings (i.e. from the SSC up to the users' ONU), such price is almost constant for all bit rate demands and for any PON technology and thus does not represent a planning decision factor in the techno-economic analysis of PON technology selection. On the other hand, the cost of the feeder fiber (i.e. from CO up to PSC) and the distribution fiber up to every building (i.e. from PSC up to SSC), present a behavior of constant increase from the point where a PON technology have to service a bit rate demand which goes beyond its limits of capacity, as illustrated in Fig. 5. This result suggests that for regions where users are sparsely located (and thus have opposite characteristics compared to the user distribution considered in this paper, which corresponds to a densely populated urban area), the cost of the ODN might represent an important decision factor in the PON technology selection.

As we have discussed in a previous Section, the hardware cost assumptions made in this paper for GPON, XGPON and NG-PON2 were obtained after interactions with system vendors, while the costs for UDWDM-PON were necessarily very approximated since this is only a "research level" technology, without any standard nor pre-production yet. We have thus performed a further analysis where we take UDWDM PON hardware costs as a variable parameter. Even though the selection of prices in this part of our analysis assumes arbitrary values, we kept such prices of UDWDM PON hardware in a feasible interval of possibilities by means of using as reference the XGPON technology. We consider three cases: first, the case when the UDWDM PON hardware is three times more expensive than the XGPON hardware; second, when it is four times more expensive than the XGPON (which correspond to the prices employed in the analysis previously presented); and third, when it is five times more expensive than the XGPON hardware. Table 12 presents the results given by OTS for these three situations. It can be observed that the prices of the UDWDM PON deployment is approximately the same for all bit rate scenarios. This is due to the fact that the six bit rate demands scenarios are far from reaching the limits of the performance for the UDWDM PON technology considered in our analysis [7].

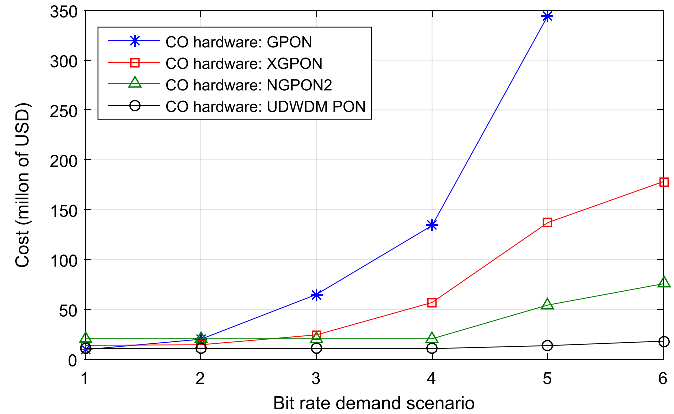

Fig. 4. Costs of CO hardware for multiple PON deployment, five CO, 10^5 users.

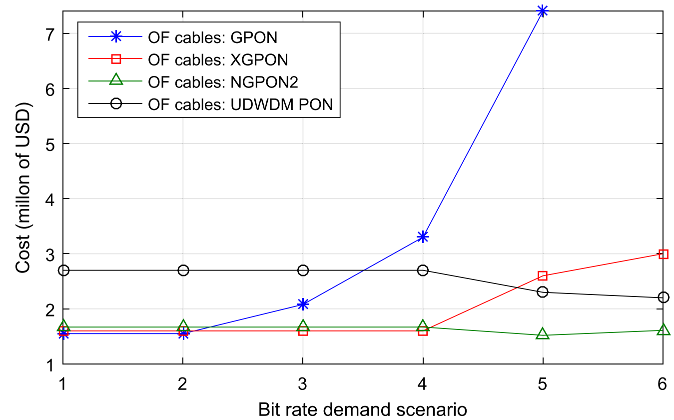

Fig. 5. Costs of feeder OF plus PSC-SSC distribution OF in the region of about 15 km^2 (Turin downtown), with 10^5 users.

Table 12
Costs of the multiple UDWDM PON deployment for three scenarios of hardware prices.

Bit Rate Scenario	Cost (millon of USD) when the UDWDM PON's hardware is:		
	$3 \times (priceXGPON)$	$4 \times (priceXGPON)$	$5 \times (priceXGPON)$
1	134.0	157.1	193.5
2	134.0	157.1	193.5
3	134.0	157.1	193.5
4	134.0	157.1	193.5
5	136.5	159.9	197.4
6	140.0	164.5	203.3

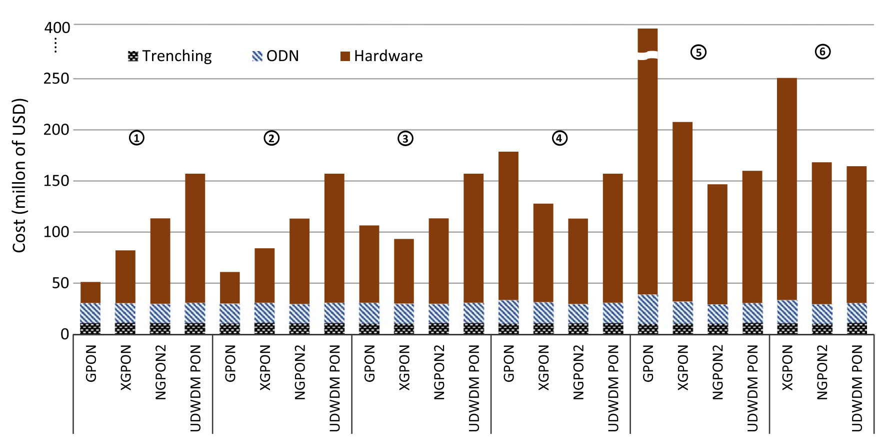

Fig. 3. Cost of multiple PON deployments for GPON, XGPON, NGPON2 and UDWDM PON in the six bit-rate-demand scenarios specified in Table 9.

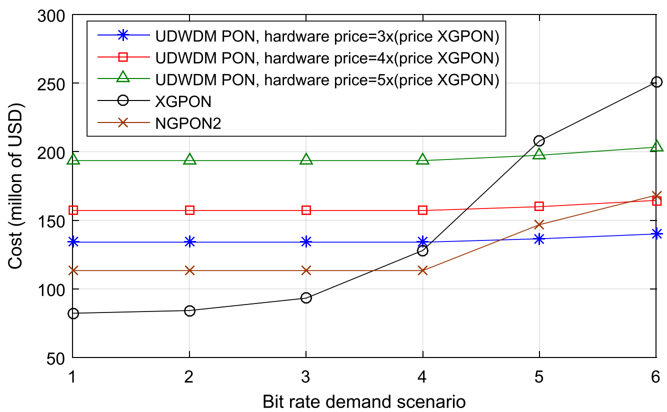

Fig. 6. Curves of multiple-PON-deployment cost vs bit-rate-demand scenario for XGPON, NGPON2 and UDWDM PON, for 10^5 users.

Fig. 6 plots the prices of Table 12 and the prices of XGPON and NGPON2 in Table 11. It can be observed that, in the six bit rate scenarios considered in the analysis, the cost of a XGPON or NGPON2 deployment increase with respect to the increase of the users' bit rate demands. And, given that the price of UDWDM PON keeps approximately constant, there is a point where UDWDM PON deployment, in any of the three considerations of hardware price, intersects with the curves of XGPON and NGPON2. Such intersection represent the approximate scenarios where a UDWDM PON solution constitutes a better option than the other PON technologies. The intersection point between XGPON curve and the lower UDWDM PON curve, in the near zone of bit-rate-demand scenario 4, suggests that if the prices of a UDWDM PON technology can be kept in a range of up to 3 times the prices of XGPON, UDWDM PON could be a better option in confront with XGPON when the users' bit rate demands reach an average value of some hundreds of Mb/s for residential users, and some units of Gb/s for business users. Instead, confronting UDWDM PON with NGPON2, results observed in the figure suggest that only when demands from users reach or goes beyond values like bit rates of scenario 5, the former could represent a equal or better solution in comparison with the latter.

5. Conclusions

A key feature of a network planning model is that it must constitute a useful tool for choosing and dimensioning the active and passive components of the network. The OTS algorithm presented in this paper is in fact a tool which satisfies this requisite. OTS is based on an effective set of heuristics which permit to obtain confident solutions for the optimal network dimensioning of PON. OTS is also versatile and can be employed in real city scenarios with very large number of users, with different bit rate demands.

The simulation analysis has revealed that UDWDM PON technology is a too expensive technology and the only way it could constitute a choice in front of other technologies is if, in the very long term scenario, residential users would demand ultra high bandwidth, like 2.5 Gb/s, and even then its feasibility would be strongly limited by the very high costs of the UDWDM PON hardware. The scenario that constitutes a point of interest for any technology deployment can be portrait in a users' bit-rate-demand basis. Thus, results obtained from our analysis employing OTS suggest that if the price of NGPON2 hardware, specially the price of the ONU, is in the range of two times the price of XGPON, then this technology constitute the best solution when users' demands reach an average from some hundreds of Mb/s up to slightly more than 1 Gb/s, for residential users. Technologies beyond NGPON2 could be interesting in longer term scenarios.

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